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**MODELING OF METHANE GAS GENERATION AND EMISSIONS FROM
LANDFILLS**

By

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By

Mahbuba Khanam

Master in Civil Engineering (MEng), Ryerson University, Toronto, Canada, 2007.

ABSTRACT

This study was carried out to develop a model capable of predicting the generation and potential emission of methane gas into the environment. Ryerson Landfill Gas Model (RLFGM) was developed using the IPCC tier two model (revised guidelines), the most recent national assessment model (Brown et. al. 1999) from UK and the model developed from DEFRA, UK. This report outlines the findings of the study and its recommendations. The study was performed on detailed characterization of solid waste as RDO, MDO and SDO and by dividing these waste components into nine waste fractions. The waste fractions are described by the percentage of moisture content of the fraction, the proportion of cellulose and hemi-cellulose, and the percentage of the degradability of the cellulose and hemi-cellulose fraction. Methane generating potential (L_0) was calculated from DOC and DOC_F value. The three methane generation rate constants (k) were used. Methane oxidation, methane correction factor, percentage of methane gas recovery, percentage of methane content in landfill gas were assumed based on comprehensive literature review. After the verification of the output of the RLFGM model with the LandGEM model it was found that the model is producing similar type of output graph as the LandGEM model but the rate of emissions of methane gas into the environment is lower in RLFGM model. It has been concluded that RLFGM model gives the realistic output with respect to individual landfill sites, taking into account of specific waste streams and deposition rates.

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First and foremost, I wish to express my sincere gratitude to Dr. Mostafa Warith, Department of Civil Engineering, Ryerson University, Toronto, Canada, my project supervisor for providing me with a great research opportunity and giving me time to time guideline and supervision to develop the model.

I would like to also extend sincere thanks to the Environment Agency UK, the Department of Environment Food and Rural Affairs (DEFRA) UK, IPCC (The Intergovernmental Panel on Climate Change), USA for their useful information to develop the model. Thanks to United States Environmental Protection Agency (US EPA) for providing me opportunity to use the landfill gas emission model (LandGEM) for the purpose of the verification of RLFGM model.

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LIST OF ACRONYMS

DEFRA	Department of Environment Food and Rural Affairs
DOC	Degradable Organic Carbon
DOC _F	Fraction Dissimilated
EPA	Environmental Protection Agency
FOD	First Order Decay
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
LandGEM	Landfill Gas Emission Model
LFG	Landfill Gas
LQM	Land Quality Management
MDO	Moderately Degradable Organic
MSW	Municipal Solid Waste
RDO	Rapidly Degradable Organic
RLFGM	Ryerson Landfill Gas Model
SDO	Slowly Degradable Organic
SWDS	Solid Waste Disposal Sites

Introduction

The latest estimation of climate change found that the temperature of the earth has been increased by 0.6°C in last hundred years (IPCC 2001). According to the Intergovernmental Panel on Climate Change, the temperature will be increasing continuously and in the next 50-100 years the temperature will increase by $5-6^{\circ}\text{C}$ (IPCC 2000). This high elevation in earth temperature will cause serious changes in climate and other environmental conditions all over the world. Some of the signs of climate changes are currently found as in the increasing amounts of rainwater and number of tropical storms. It is strongly believed by researchers and scientists that one of the most important sources of greenhouse gas is MSW landfill gas. MSW landfill gas is primarily composed of methane and carbon dioxide. Methane is about 21 times stronger greenhouse gas than carbon dioxide.

The use of landfills for MSW disposal is expected to increase in United States, Australia and many developing nations (Bogner, et al. 2000). About 55% of all MSW generated in U.S.A is currently being disposed in approximately 2,300 municipal landfills (EPA 1998a). The U.S.A generated approximately 220 million tons of MSW in 1998 (EPA. 1998b). The estimated release of methane gas was approximately 9×10^5 mg/year (Eklund, et al. 1998).

As the methane gas emission from landfills is causing serious harm to the environment of the world, currently more attention has been drawn in landfill gas recovery. It reduces greenhouse gas emissions and creates an alternative renewable source of energy through the systematic recovery and utilization of landfill gas (Alexander Klein, 2002). Methane gas provides a potential renewable power source (Pembina Institute, 2003). One cubic metre of waste has an energy value of 4 to 5 kilowatts (kwh) or 0.5 litres of heating oil (Thompson and Tanapat, 2004; Tanapat and Thompson, 2003; Tanapat et al, 2003). In Canada, methane gas recovery from landfill gases is one of the most cost effective means to reduce greenhouse gas emissions. Currently forty-one landfills in Canada are capable to capture methane gas. This methane gas recovery results in an annual reduction of GHG (Greenhouse Gas) emissions of more than 7 megatonnes/year of carbon dioxide equivalents (Environment Canada, 2001). Approximately 70 percent of the captured gas in Canada is used for energy generation at 13 facilities and six of them generate electricity to sell to the grid (e.g., Keele St. Landfill in Toronto). Other seven facilities use the gas directly as an industrial process fuel (Environment Canada, 2001).

Many researches have been performed on landfill gas generation and emission to help to estimate the amount of generation and emission of landfill gases. This estimates help to develop the landfill gas recovery systems. After studying the models on landfill gas generation and emission from landfills the developer of the RLFGM model has found that in North America the research is mostly focused on rate of deposition of solid waste into landfills. But European researchers consider individual waste category as well as the deposition rate of municipal solid waste into landfills. The developer of the RLFGM model believes this concept as more realistic approach to estimate the rate of generation and emission of methane gas from landfills. This persuaded the developer to focus research on the rate of deposition of MSW into landfills considering individual waste stream category. RLFGM model was developed for well-managed engineered landfills in North America.

This report focuses on developing a computer model to estimate the generation of methane gas and emission from landfills into the environment.

1.1 Related works

Landfill gas generation and emission into the environment is a very important issue today with respect to protect the environment of the current world. Many researches have been performed for the estimation of generation and emission of landfill gas in the past decades. For the purpose of development of the RLFGM model ten computer models have been studied. Studied models are from US EPA, IPCC, Environmental Protection Agency UK, the model developed from Department of Environment Food and Rural Affairs (DEFRA), UK and some other models. Among the studied models nine have been summarised in Appendix A (Tables 1 to 4).

2. Main Body

2.1. RLFGM - Ryerson Landfill Gas Model

RLFGM model is an excel spreadsheet model for a well-managed engineered landfill developed at Ryerson University, Toronto, Canada. The model provides a simple approach to estimate methane gas generation and emission from landfills. The model has been coded using the Microsoft Visual Basic and Excel. The RLFGM model has been developed for the simulation period of thirty years.

RLFGM model has been designed using the help of IPCC tier two model (revised guidelines), the most recent national assessment model (Brown et. al. 1999) from UK and the model developed by LQM for the Department of Environment Food and Rural Affairs (DEFRA), UK. The national assessment model and LQM model are also based on IPCC tier two model with UK-specific modifications. But LQM added some more work on the determination of degradable organic carbon (DOC) and fraction dissimilated (DOC_F) and methane oxidation in addition to the national assessment model (Brown et. al. 1999). The model has been validated using the landfill gas emission model (LandGEM). RLFGM model estimates the maximum expected methane gas generation and emission potential based on factors such as the waste acceptance rates, methane generation rate constants (k), and methane generation potential (L_0).

Relevant data regarding the different waste composition and different degradability rate for municipal solid waste was used during the development of the RLFGM model. The calculation of degradable organic carbon (DOC) and fraction dissimilated (DOC_F) were considered from the LQM model developed from Department of Environment Food and Rural Affairs (DEFRA), UK. Methane generation potential (L_0) was calculated using the $DOC \cdot DOC_F$ value. Three methane generation rate constants (rapidly degradable organic, moderately degradable organic and slowly degradable organic) were used in the design of RLFGM model considering the approach developed in the GasSim model. The model enables users to produce typical methane generation and emission rate from a well-managed engineered landfill located in North America.

2.2. Limitations of the model

- The RLFGM model was developed considering the landfills scenario in North America. It could be assumed that landfills in North America are well-managed as well as engineered landfills. It cannot be used for un-managed, non-engineered landfills.
- Lignin component was not considered in the simulation of the parameters $DOC(x) \cdot DOC_F$.

2.3. Waste category used in the simulation of RLFGM model

The model was implemented by dividing the wastes into three degradability of waste category as slowly degradable, moderately degradable and rapidly degradable wastes. These three waste

categories divided the waste streams into nine waste fractions as displayed in Appendix A, Table 5. The model characterizes the biodegradability of the rapidly, moderately and slowly degradable wastes by means of three main parameters as SDO (slowly degradable organic), MDO (moderately degradable organic) and RDO (rapidly degradable organic).

2.4. RLFGM conceptual model

RLFGM conceptual model has a modular structure, see Figure 1. The conceptual model is divided into four modules as below:

- i) Methane Oxidation;
- ii) Source;
- iii) Methane Utilization and
- iv) Methane emission into the environment;

The modules are described below:

i) Methane oxidation: RLFGM model was developed for a well-managed, engineered landfill in North America. According to IPCC (2000), the model used 0.1 as its oxidation factor (OX term in equation 2.4) for its implementation purpose.

ii) Source: The heart of the model is the source term. The source term simulates the generation of methane gas taking into account the following waste characteristics:

- The waste breakdown, the mix of different municipal solid waste fractions;
- The waste composition e.g. the proportion of rapidly degradable organic (paper, textiles, misc. combustible plus non-inert, composted putrescible), moderately degradable organic (ferrous and non ferrous metals), and slowly degradable organic (dense plastics, misc. combustible plus inert fines and glass). The waste composition is defined by the percentage of moisture content of the fraction, the proportion of cellulose and hemi-cellulose, as well as the percentage of the degradability of the cellulose and hemi-cellulose fraction, see Appendix A, Table 6.
- Physical parameters of waste;
- The biodegradability of the waste fractions (rapidly degradable organic, moderately degradable organic, slowly degradable organic), the rate of decay of waste fractions. The methanogenic degradation of carbon is simulated by dividing the different waste streams into three waste

categories. These waste categories are divided into nine waste fractions (Appendix A, Table 5), as rapidly degradable organic (RDO – paper, textiles, misc. combustible (plus non inert), composted putrescible), moderately degradable organic (MDO - ferrous and non ferrous metals), and slowly degradable organic (SDO – dense plastics, misc. combustible (plus inert fines) and glass). The gas generation is then calculated using highly flexible multi-phases equations (Equations 2.1 to 2.3).

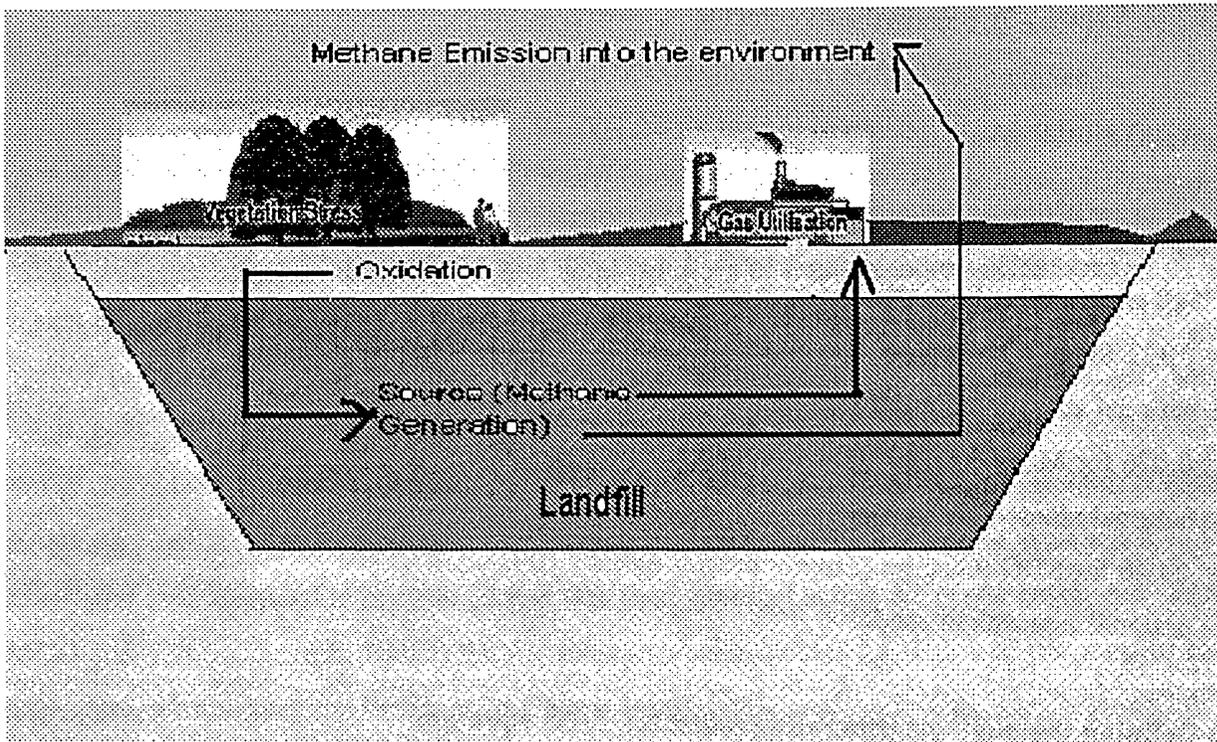


Figure 1 RLFGM conceptual model

Defining equations: RLFGM model used multilevel phases of equations for the generation of methane gas in landfills. The model used IPCC tier two model (revised guidelines), the latest national assessment model (Brown et. al. 1999) from UK and LQM model from the Department of Environment Food and Rural Affairs (DEFRA), UK.

The Revised IPCC (Guidelines for National Greenhouse Gas Inventions, 2000) tier two model is a first order decay (FOD) model. The model produces a time dependent emission profile that reflects the true pattern of the degradation process over time. The tier two methodology is described by the equations 2.1 – 2.2 below.

a) Defining the rate of methane gas generation equation:

• Methane gas generated in year (Gg/yr) = $\sum_x [(A.k(MSW_T(x).MSW_F(x).L_0(x)).e^{-k(t-x)})]$
for x = initial year to year t..... (2.1)
(Eq. 5.1 in IPCC 2000)

Where

- t = year of inventory
- x = years for which input data should be added
- A = $(1 - e^{-k})$, a normalization factor
- k = methane generation rate constant (l/yr)
- MSW_T(x) = total MSW generated in year x (Gg/yr)
- MSW_F(x) = fraction of MSW disposed into solid waste disposal sites (SWDS) in year x (Gg/yr)

Assumptions:

- 62% of generated solid waste is disposed into landfill
- k = 0.116 for RDO (GasSim (Environmental Agency 2002a, UK)), and the current data set for the national assessment model
- k = 0.076 for MDO (GasSim (Environmental Agency 2002a, UK)), and the current data set for the national assessment model
- k = 0.046 for SDO (GasSim (Environmental Agency 2002a, UK)), and the current data set for the national assessment model

b) Defining the methane generating potential, L₀(x) equation:

• $L_0(x) = [MCF(x). DOC(x)DOC_F.F.16/12]$ (Gg CH₄/Gg Waste) national assessment model, UK
.....(2.2)

Where

- MCF(x) = methane correction factor in year, x (fraction)
- DOC(x) = degradable organic carbon (DOC) in year, x (fraction) (Gg C/Gg waste)
- DOC_F = fraction of DOC dissimilated
- F = fraction by volume of methane gas in LFG
- 16/12 = conversion from carbon to methane

Assumptions:

MCF(x) = 1.0 (considering managed solid waste disposal site)

$$F = 0.5$$

c) Defining degradable organic carbon (DOC) and fraction dissimilated (DOC_F): This is accepted from the LQM model from Department of Environment Food and Rural Affairs (DEFRA), UK.

Defining Equation:

$$\bullet (\text{DOC}(x) \cdot \text{DOC}_F)_{ij} = M(x)_{ij} \cdot (\%C_i + \%HC_i) \cdot \%DC_i \cdot (1 - \%MC_i) \cdot 72/162 \text{ (Gg C/Gg waste)}$$

.....(2.3)

Where

$M(x)_{ij}$ = mass of waste category in year x, degradability fraction j (Gg waste)

$\%C_i$ = cellulose content of waste category i (fraction)(Gg cellulose/Gg waste)

$\%HC_i$ = hemi-cellulose content of waste category i (fraction) (Gg hemi-cellulose/Gg waste)

$\%DC_i$ = degradability of the cellulose and hemi-cellulose of waste category i (fraction)

$\%MC_i$ = moisture content of waste category i (fraction)

72/162 = conversion from cellulose/hemi-cellulose to carbon (Gg C/Gg cellulose and hemi-cellulose)

Total degradable organic carbon that is dissimilated within each waste fraction (rapidly, moderately and slowly degradable organic) was calculated separately using the equation 2.3. The calculated total degradable organic carbon was then summed across all waste categories (RDO, MDO and SDO). The term $\text{DOC}(x) \cdot \text{DOC}_F$ does vary with time as a function of the mass of each individual waste category but does not vary significantly with cellulose and hemi-cellulose contents, moisture contents of individual waste category. RLFGM model adopted this equation and the concept for its implementation. The $\text{DOC}(x) \cdot \text{DOC}_F$ value was used to derive the specific methane generating potential, L_0 for each waste fraction. Total methane generating potential was calculated by the addition of the previous years L_0 value with the current year L_0 value. It was accepted accounting the concepts that the waste already disposed into the landfill yet generating the methane gas. This methane generating potential value provides the input into equation 2.1 mentioned, to obtain the value of the methane gas generated in each year.

iii) Methane utilization: According to the current US EPA regulations under the Clean Air Act, many larger landfills require to collect and combust landfill gas. The options available are flaring the gas or installing a landfill gas recovery and utilization system. There are a number of

environmental and economic benefits of recovering landfill gas. Gas recovery systems reduce landfill gas odor and migration of landfill gas, reduce the danger of explosion and fire. The recovered methane gas is also a very good source for the generation of electricity in the current world. According to UK's national assessment, it was estimated that in the year of 2002 at least 63% of the total landfill gas generated in UK was flared or utilized and it increased to approximately 72% by 2005. During the development of the RLFGM model it was assumed that 72% of methane gas would be recovered.

iv) Methane gas emission from landfills: Methane gas emission from landfills is normally controlled by engineering measures, e.g. the installation of engineered barriers (cap and liner) and gas collection systems. RLFGM model determined methane gas emissions from landfills based on comprehensive literature review. The RLFGM model assumes that methane gas generated and not collected would be emitted through the landfill cap or liner at a steady state and would be released into the surface to the atmosphere. RLFGM model assumes that 72% of methane gas recovery for its development purpose. RLFGM model reduces the emission of methane gas through the cap by biological methane gas oxidation. The model allows the use of the IPCC (2000) methodology which states that the oxidation factor for a well-managed landfill should be 0.1 based on available information. RLFGM model assumes oxidation factor as 0.1 for its design purpose. Assuming 72% recovery of methane gas and oxidation factor as 0.1 the model uses the IPCC (2000) tier two model for the calculation of methane gas emission into the environment. The equation is shown below:

Defining Equation:

- Methane emitted in year t (Gg/yr) = $[CH_4 \text{ generated in year } t - R(t)] \cdot (1 - OX) \dots \dots \dots (2.4)$
 (Eq. 5.2 in IPCC 2000)

Where

R(t) = recovered methane gas in inventory year t (Gg/yr)

OX = oxidation factor

Assumptions:

Landfill gas recovered (flared or utilized) = 72% of the landfill gas generated

Oxidation Factor (methane oxidation) = 0.1

2.5. Model parameters

i) Methane generation rate constants, k: RLFGM model used three methane gas generation rate constants for RDO, MDO and SDO components accounting the approach developed for the Environmental Agency's GasSim model, UK. For methane generation rate constant, k the IPCC (2000) proposed a single value of k as 0.05 per year corresponding to a half-life period of 15 years. Manely et al. (1990a; 1990b) first used three rate constants for slowly degradable, moderately degradable, and rapidly degradable wastes, and Brown et al. (1999) introduced three rate constants into the national assessment model, UK. The methane generation rate constants used by Manely et al. (1990a; 1990b), Brown et al. (1999) and GasSim models are given in Appendix A, Table 7. It was noted that in all cases, the half-life period of the slowly degradable organic is consistent with the IPCC (2000) value 0.05. The half-life period for rapidly and moderately degradable wastes was increased. It has been found from comprehensive literature review that it has been accounted to avoid immediate peaks corresponding to short half-lives period in the simulation.

ii) Methane Correction Factor, MCF: Unmanaged solid waste disposal sites (SWDS) produce less methane gas compared to managed SWDS. It is because of a larger fraction of waste decomposes aerobically in the top layers of unmanaged SWDS. According to IPCC (2000), (Appendix A, Table 8) the methane correction factor for a managed SWDS should be 1.0. Values less than 1.0 may be adopted for developing or countries with unmanaged solid waste disposal sites. It is assumed that in North America all landfills are well-managed and engineered landfills. For that reason RLFGM model used 1.0 as its methane correction factor value during its development.

iii) Methane Oxidation, OX: According to IPCC (2000) the oxidation factor for well-managed landfills at a national level should be 0.1. Considering that approach the model assumed 0.10 as its methane oxidation factor value for its implementation.

iv) Methane Content in LFG, F (percentage by volume): Typical landfill gas composition is shown in Appendix A, Table 9. The landfill gas composition is influenced by the decomposition of landfill solid waste. The decomposition of biodegradable waste in landfills gives rise to both methane gas and carbon dioxide in approximately equal quantity by volume. The mechanics of this process are governed by a number of different biochemically mediated reactions (AFRC,

1988). It could be said that the actual quantity of methane gas or carbon dioxide produced by decomposition will vary according to the dominant microbiological processes. In older uncapped sites, natural diffusion of air through the cover materials led to a greater degree of aerobic degradation, and thus the proportion of methane gas produced changed from 50:50. This reflected the increased carbon dioxide and reduced methane gas production. For an older un-engineered not well-managed landfill the percentage of methane gas content in LFG may be of 30%. The RLFGM model used a methane gas content of 50% in LFG for its investigation purpose. For the purpose of developing the RLFGM model, a value of 0.5 for methane gas content in LFG has been accepted.

v) Degradable organic carbon (DOC) and fraction dissimilated (DOC_F): The IPCC states that the fraction of the degradable organic carbon that actually degrades to release methane gas and carbon dioxide should be by default 0.77 (if lignin is excluded from the DOC) or between 0.5-0.6 (if lignin is included). But the LQM model from Department of Environment Food and Rural Affairs (DEFRA), UK used the equation 2.3 for the calculation of total degradable organic carbon that is dissimilated within each waste fraction (rapidly, moderately and slowly degradable organic). The model calculated it separately and used for its implementation. The RLFGM model used this approach for its study purpose. The methanogenic degradation of carbon was implemented by dividing the different waste streams into three waste categories (Appendix A, Table 5), as RDO – (paper, textiles, misc. combustible plus non inert, composted putrescible), MDO – (ferrous and non ferrous metals), and SDO – (dense plastics, misc. combustible plus inert fines and glass).

The term $DOC(x) \cdot DOC_F$ was calculated based on moisture content, cellulose, hemi-cellulose and degradability fraction of cellulose and hemi-cellulose of individual waste category. Typical MSW contains cellulose, hemi-cellulose and lignin (Barlaz et al., 1990) components. Cellulose and hemi-cellulose account for 91 percent of the methane gas potential in MSW (Barlaz et al. 1989). The model does not consider lignin component for its study purpose. Some researchers (Eleazer et al., 1997) found that the lignin degrades slowly under anaerobic conditions. Some other researchers have demonstrated that lignin has no methane gas generating potential because it is recalcitrant under the anaerobic conditions (Young and Frazer 1987). Based on these studies it was decided not to consider the lignin component for the investigation of the RLFGM model.

3. Results and Discussions

This section discusses the output provided by the model. Three steps have been adopted for the generation and emission of methane gas in RLFGM model.

i) $DOC(x).DOC_F$: $DOC(x).DOC_F$ value has been calculated using the equation 2.3 in the implementation of RLFGM model. It has been calculated for different waste streams category (Appendix A, Table 5). A sample model output is shown in Appendix A, Table 10, which is based on data input in Appendix A, Table 6.

$DOC(x).DOC_F$ does vary with time with respect to mass of solid waste disposed into landfills. It does not vary significantly with moisture content, cellulose, hemi-cellulose and degradability fraction of cellulose and hemi-cellulose of individual waste category. This was assumed in the design of the RLFGM model.

ii) Methane generating potential, L_0 : The methane gas generating potential L_0 has been calculated using the equation 2.2. It used $DOC(x).DOC_F$ values as input values. Calculated values were summed up for each degradability rate (RDO, MDO, SDO). During the implementation of RLFGM model it has been assumed that the solid waste already disposed into landfill yet producing the methane gas. So it added the L_0 of the current year to the previous years. The Table 11 in Appendix A shows the sample output of L_0 of the model simulation.

iii) Methane gas generation and emission rates from landfills: The above equation 2.1 and equation 2.4 have been used for the generation and emission of methane gas from landfills. One set of municipal solid waste data (Appendix A, Table 6) has been used for the simulation of methane gas generation and emission from landfills. It has been assumed from current practice that 62% of the generated solid waste would be disposed into landfills and 72% of the landfill gas generated would be recovered (flared or utilized). The rate of methane gas generation and emission from landfill has been displayed in graphs (see Figure 2 and Figure 3). During the 30 years (from 1995 to 2025) simulation period from year 1998 to year 2007 methane gas generation rate was high. Methane gas emission rate was high from year 1998 to year 2011. Rate of methane gas generation and emission from landfill both have decreased with time after that period. The highest methane gas generation rate and emission rate were found in the year of 2000.

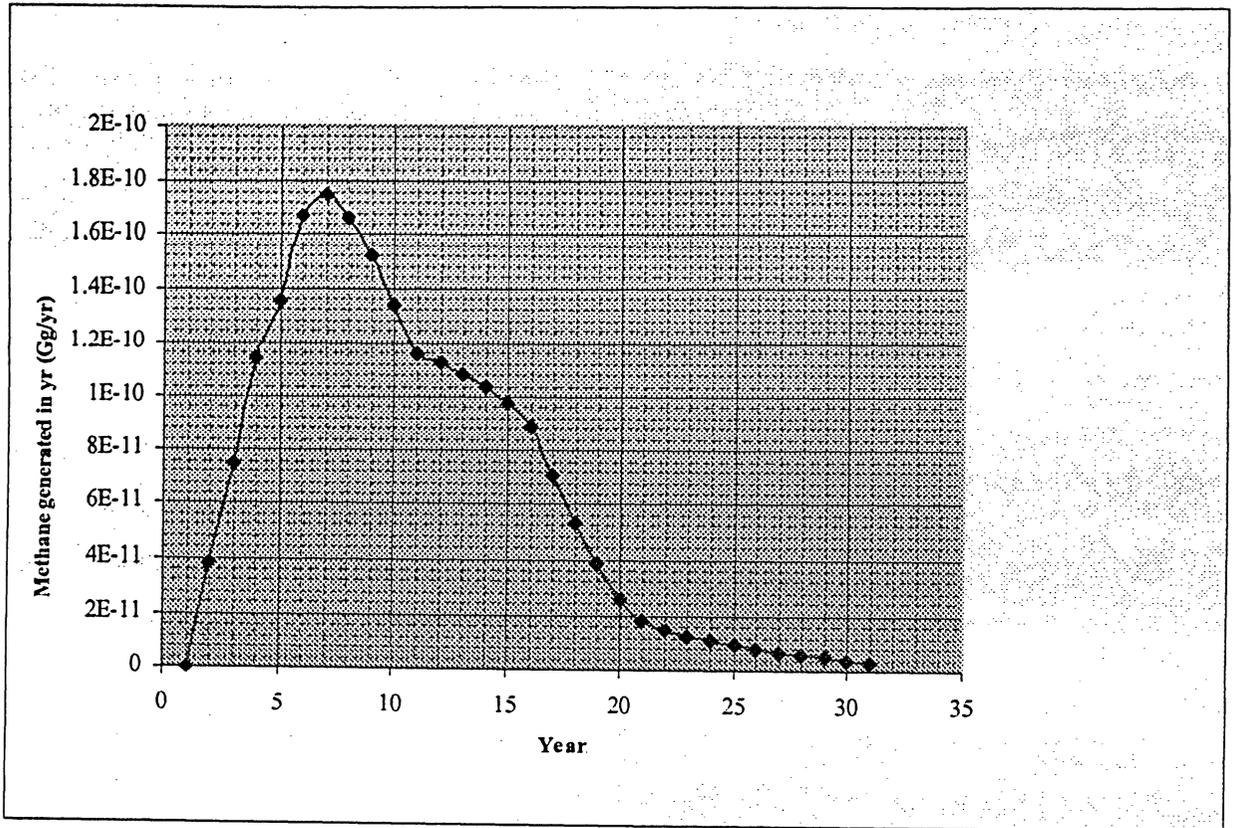


Figure 2 Analysis of methane gas generation rate (Gg/yr) from landfill

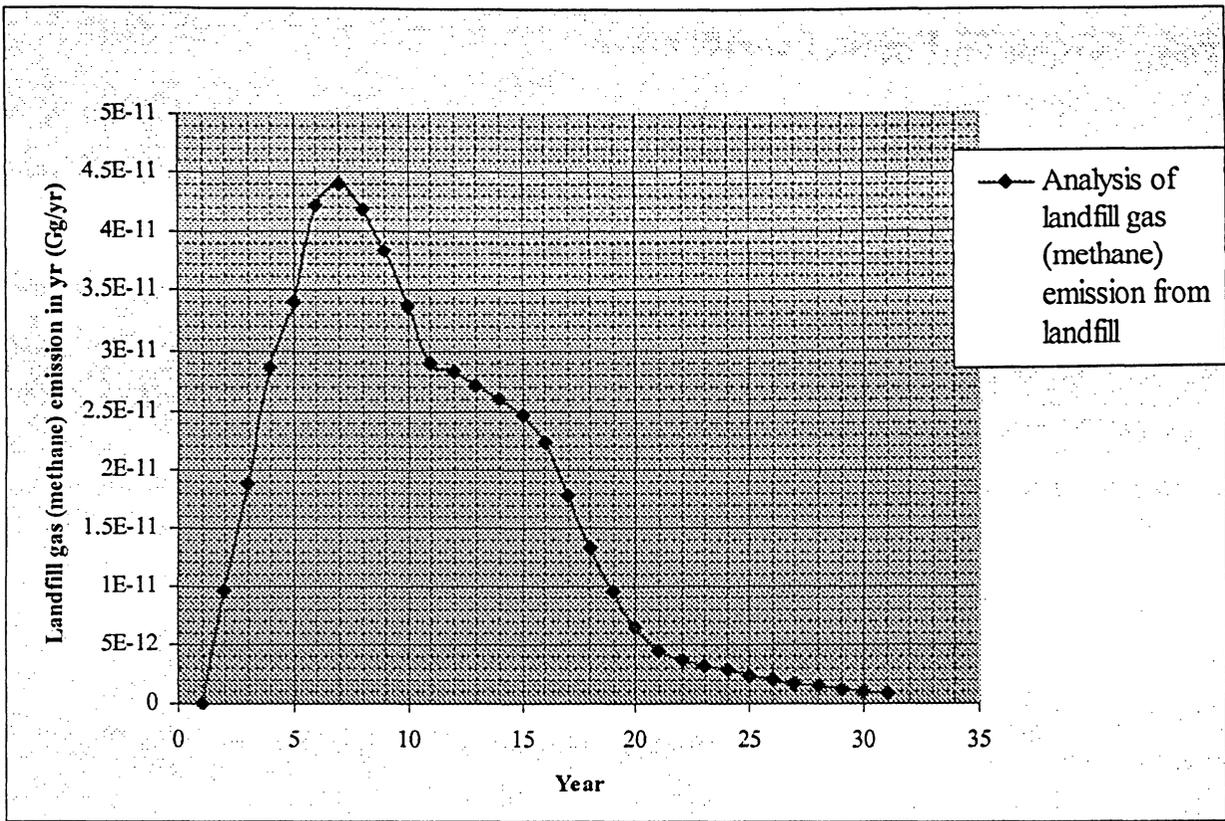


Figure 3 Analysis of methane gas emission rate (Gg/yr) from landfill

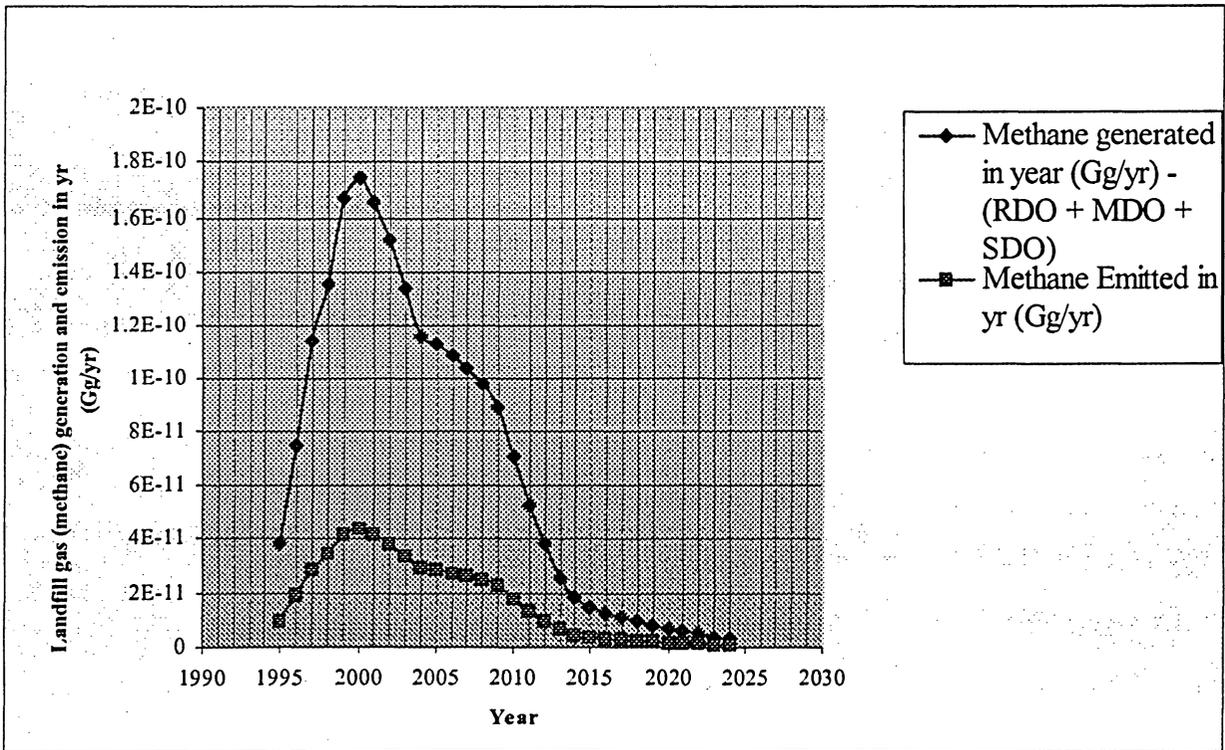


Figure 4 Comparing methane gas generation and emission rate (Gg/yr) from landfill

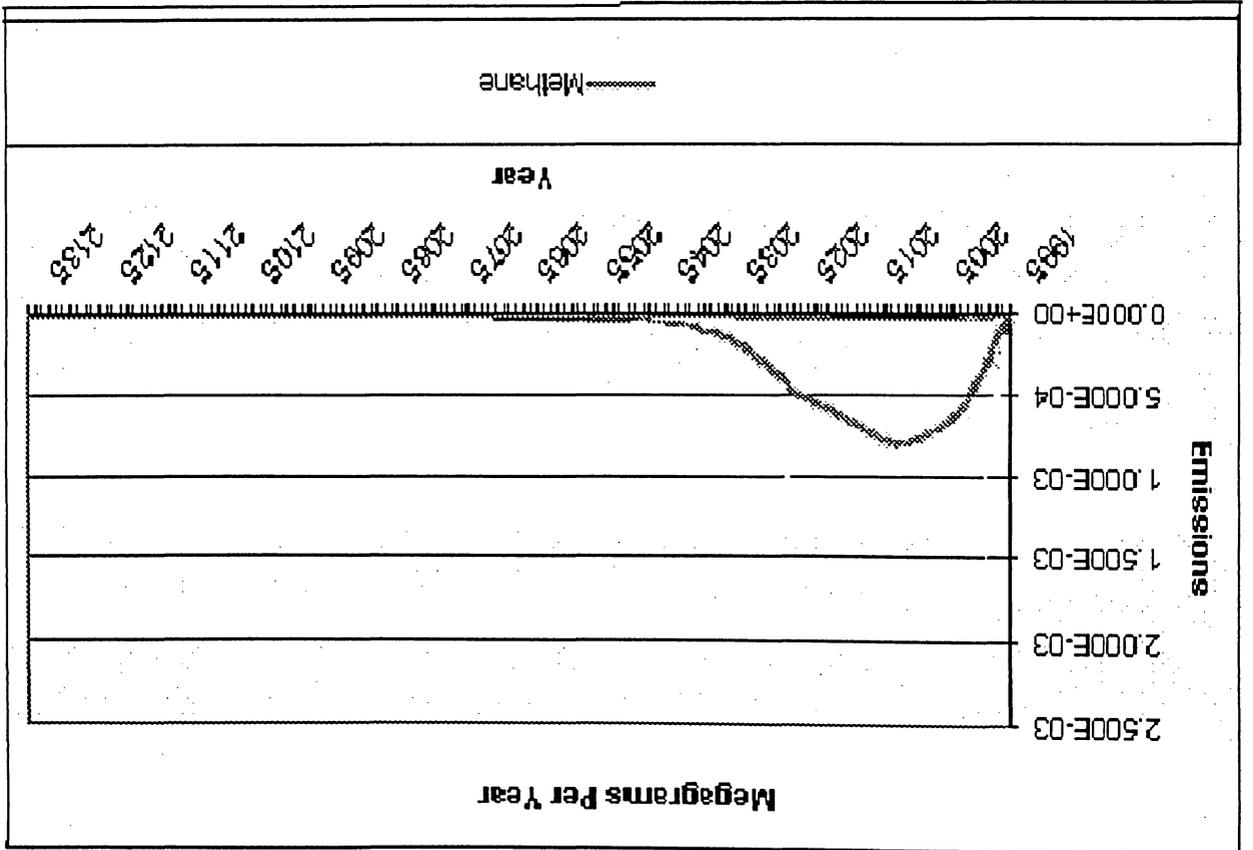
4. Data inputs and model verification

The model verification has been performed by comparing the output of the RLFGM model with the LandGEM model from US EPA. The LandGEM model uses the first order decay (FOD) equation (Appendix A, Table 1) where as RLFGM model uses multi-phases equations for the generation and emission of methane gas from landfills. The LandGEM model has been simulated using the same set of solid waste mass input data from Appendix A, Table 6. While simulating the LandGEM model only RDO component of the waste from Appendix A, Table 6 has been accepted. It excluded the MDO and SDO components as moderately degradable organic and slowly degradable organic may not produce methane gas.

The major difference between the models is the calculation steps of the methane gas generating potential (L_0). The LandGEM model uses the constant values as CAA conventional $170 \text{ m}^3/\text{Mg}$, CAA arid area $170 \text{ m}^3/\text{Mg}$, inventory conventional $100 \text{ m}^3/\text{Mg}$, inventory arid area $100 \text{ m}^3/\text{Mg}$, inventory wet $96 \text{ m}^3/\text{Mg}$. For the verification purpose $100 \text{ m}^3/\text{Mg}$ has been used for LandGEM model simulation accounting inventory conventional approach.

The RLFGM model considers different components (RDO, MDO and SDO components) of waste streams (Appendix A, Table 6) and calculated the $\text{DOC}(x).\text{DOC}_F$ value separately. The summation of $\text{DOC}(x).\text{DOC}_F$ value of all components was used for the implementation of L_0 value. The calculation of methane gas generation has been accomplished by the addition of L_0 value of the current year with the previous years. This value is lower than the L_0 ($100 \text{ m}^3/\text{Mg}$) value from the LandGEM model making the model output lower. The output graph for the methane gas emission of both of the models resembles similar, see Figure 4 and Figure 5. The model output for methane gas emission from landfills for both of the models are compared in Appendix A, Table 13. It has been found that for the RLFGM model maximum methane gas emission from landfills has occurred in the year the of 2000 and for LandGEM it has occurred in the year of 2011. The parameters used for the simulation of LandGEM model are shown in Appendix A, Table 12. A comparing table (Appendix A, Table 14) has been shown to focus the differences between RLFGM model and LandGEM model simulation parameters and results.

Figure 5 LandGEM model output for methane gas emission from landfill



5. Conclusion

RLFGM model has been developed for the purpose of the generation and emission of methane gas from landfills. The model has been constructed using the help of IPCC tier two model (revised guidelines), the most recent national assessment model (Brown et. al. 1999) from UK and the LQM model developed from the Department of Environment Food and Rural Affairs (DEFRA), UK. The model was validated using the help of LandGEM model. The implementation was performed with some model-defined data sets as well as some user-defined data sets. The data sets used are methane gas generation rate constants, k for rapidly degradable organic, moderately degradable organic and slowly degradable organic, methane correction factor and methane oxidation. The user-defined data sets are yearly rate of solid waste disposal into landfills. Degradable organic carbon (DOC) and fraction dissimilated (DOC_F) were calculated using the model input data and used for the calculation of methane generating potential (L_0). During the validation of the RLFGM model using the help of the LandGEM model it was found that the output graph for the methane gas emission from landfill resembled similar with the LandGEM model output but the value was smaller. The RLFGM model calculates the methane gas generation and emission rate considering three types of waste degradability fraction as rapidly degradable organic, moderately degradable organic and slowly degradable organic. The waste fractions are described by the moisture content, cellulose content, hemi-cellulose content of the waste fraction, degradability of the cellulose and hemi-cellulose of waste category. It was found that it gives the realistic output with respect to individual landfill site, taking into account of specific waste streams and deposition rates. It has been concluded as one of the greatest benefits of the RLFGM model.

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Appendix A:

Table 1 Summary of the landfill gas generation and emission models from United States Environmental Protection Agency (US EPA)

Model Name	Landfill gas emissions model
Team	US EPA (1998)
Equation used	$Q_T = \sum_{i=1}^N 2 k L_0 M_i e^{-k t_i}$ <p> Q_T = total gas emission rate from a landfill, mass/time k = landfill gas emission constant time⁻¹ L_0 = methane generation potential, volume/mass of waste t_i = age of the ith section of waste, time M_i = mass of wet waste, placed at time i N = total time period of waste placement </p>
Components incorporated with the model	<p>This model is based on a first-order decomposition model. There is a choice in the model between “Codisposal” and “No Codisposal”.</p> <p>Assumptions:</p> <ol style="list-style-type: none"> 1. The model assumes that CO₂ gas emission rates are the same as the methane gas emission rates. 2. Landfill gas emission rates are twice the methane gas emission rates. 3. The generation of methane gas from a landfill is a function of two values: k, the methane gas generation rate and L_0, the methane gas generation potential and they are considered constants values. 4. Two different set of model default values used for the calculation of emissions: a set of default values for determining applicability of the NSPS or emission guidelines (the CAA defaults) for MSW landfills and a set of default values based on emission factors from AP-42 (the AP-42 defaults). <p>Limitation:</p> <ol style="list-style-type: none"> 1. A more sophisticated calculation method was not justified because of the limitation of the data availability for landfills, such as data on the quantity, age, and deposition refuse in the landfills.

Model Name	First Order Decay model (FOD)
Team	US Environmental Protection Agency (EPA)
Equation used	<p>1. Total amount of landfill gas generated in current year,</p> <ul style="list-style-type: none"> • $Q_T = 2L_0R(e^{-kc} - e^{-kt})$ • $Q_T = \sum_{i=1}^n 2kL_0M_i e^{-kti}$
Components incorporated with the model	<p>Assumptions:</p> <ol style="list-style-type: none"> 1. Requires as input solid waste disposal data including (for past 20-25 or more years). Data inputs are: <ul style="list-style-type: none"> • Composition of the waste and • Conditions at the SWDS. 2. The parameters used are – <ul style="list-style-type: none"> k = Methane generation rate constant L_0 = Total methane generation potential of the waste $= (MCF \cdot DOC \cdot DOC_F \cdot F \cdot 16/12)$ 3. The rate of degradation for waste disposed at SWDS needs to be determined. 4. FOD method takes the timing of the emissions into consideration and gives a more realistic picture of the actual emissions during the inventory year in question. <p>Limitations:</p> <ol style="list-style-type: none"> 1. Default values needed in the FOD method are insufficient. 3. The FOD method considers the time factor of the degradation process and produces annual emission estimates that reflect this process. This process can take years, even decades.

Table 2 Summary of the landfill gas generation and emission models from the Intergovernmental Panel on Climate Change (IPCC)

Model Name	IPCC Default model IPCC guidelines, 1996)
Team	The Intergovernmental Panel on Climate Change (IPCC, 1996)

<p>Equations used</p>	<ol style="list-style-type: none"> 1. Methane gas emissions (Gg/yr) = $(MSW_T \cdot MSW_F \cdot MCF \cdot DOC \cdot DOC_F \cdot F \cdot 16/12 \cdot R) \cdot (1 - OX)$ 2. DOC (Degradable organic Carbon) = $0.4 \cdot (A) + 0.17 \cdot (B) + 0.15 \cdot (C) + 0.30 \cdot (D)$ 3. DOC_F (Fraction DOC dissimilated) = $0.014 \cdot T + 0.28$ 4. F = fraction of methane in landfill gas, 50% (IPCC default value) 5. OX = oxidation factor, 0 (IPCC default value). 6. Methane Correction Factor = $[1/(1+R)^T] \cdot \{1 - 1/[T \cdot \ln(1 + R)]\}$ 7. MSW_F (Fraction of MSW disposed into solid waste disposal sites) = $(MSW_T \cdot CC) \cdot SW_{TREAT} \cdot MSW_{REC}$
<p>Components incorporated with the model</p>	<p>IPCC default method is a simple, transparent and easy to use. IPCC default method can produce relatively good estimates of the potential future emissions.</p> <p>Assumptions:</p> <ol style="list-style-type: none"> 1. The model requires only input of a limited set of parameters. The input parameters are: <ul style="list-style-type: none"> • The composition of the waste and • The conditions of the SWDS. 2. The model does not need to determine the rate of decomposition of waste at SWDS. The IPCC guidelines contain the default values for the most of the data needed in the model. <p>Limitations:</p> <ol style="list-style-type: none"> 1. IPCC default methodology provides estimates on potential methane gas emissions without incorporating any time factors. 2. The method will produce fairly good estimates of the yearly emissions if the yearly amounts as well as composition of waste disposed have been nearly constant for long periods. Increasing amounts of waste disposed will lead to an overestimation, and decreasing amounts correspondingly to underestimation of yearly emissions. 3. The uncertainties in the emission estimates produced by IPCC method are

	large in most countries. 4. Need improved reporting schemes regarding LFG recovery plants.
Model name	IPCC tier two model (2000)
Team	IPCC (The Intergovernmental Panel on Climate Change) revised guidelines
Equations used	1. Methane gas generated in year t (Gg/yr) = $\sum_x [(A. k. MSW_T(x). MSW_F(x). L_0(x)).e^{-k(t-x)}]$ 2. Methane gas generating potential, $L_0(x) = [MCF_{(x)}.DOC_{(x)}. DOC_{(F)}. F. 16/12](Gg CH_4/Gg waste)$ 3. Methane gas emitted in year t (Gg/yr) = $[CH_4 generated in year t - R (t)]. (1-OX)$
Components incorporated with the model	Assumptions: 1. IPCC tier two model is a first order decay (FOD) model. The model considers time to determine emission profile that reflects the true pattern of the degradation process over time. 2. Tier two model does site specific NMOC concentration measurements.

Table 3 Summary of the landfill gas generation and emission models from Environment Agency, UK and the model developed from the Department of Environment Food and Rural Affairs (DEFRA), UK.

Model name	GasSim (Landfill Gas Risk Assessment Tool), developed for Environment Agency (England), 2002a
Team	Golder Associates (UK) Ltd and LQM (Land Quality Management)
Equations used	<p>1. Gas Generation (Bulk Gas):</p> <ul style="list-style-type: none"> $C_t = C_0 - (C_{0,1}e^{(-k_1t)} + C_{0,2}e^{(-k_2t)} + C_{0,3} e^{(-k_3t)})$ $C_x = C_t - C_{t-1}$ (following LandGEM) $C_t = C_0 - (C_{0,1}e^{(-k_1t)})$ and $C_x = C_t - C_{t-1}$ <p>2. The emissions of LFG through</p> <p>4. Flares/Gas Utilization Emissions:</p> <ul style="list-style-type: none"> $R_{pc} = (Q_{engine \text{ or } Q_{flare}}).G_p. (1 - DE\%/100\%)$ $RCO_2c = (Q_{engine \text{ or } Q_{flare}}). [(G_{CH_4}). 44/16]. (DE\%_{CH_4}/100\%) + [(G_{VOC}) . 44/14] . (DE\%_{VOC}/100\%)$ $R_{pc} = (A_F + 1) . ([F_p]. F + [E_p].E)$ $R_D = (Q_{engine \text{ or } Q_{flare}}).[G_p].$

	<p>the cap and the liner: MM.(DE%/100%</p> <p>$Q_c = Q_{res}/[(d_c/K_c.A_c).(K_l.A_l/d_l)+1]$ 3. Migration of gas:</p> <p>$Q_l = Q_{res}/[(d_l/(K_l.A_l)).((K_c.A_c)/d_c)+1]$ $\partial_c/\partial_t = D_L(\partial^2c/\partial^2x) - v(\partial_c/\partial_x) - \gamma c$</p>
<p>Components incorporated with the model</p>	<p>GasSim is a computer model. It has been encoded using Microsoft Visual Basic and C++ programming languages. GasSim model has been developed using the HELGA framework (Gregory et al., 1999), which was developed for the Environment Agency, England. The Monte Carlo simulation technique was used to model the uncertainty associated with many of the input parameters. Environmental transport is simulated using (Gaussian plume) model. GasSim is a steady state model.</p> <p>Assumptions:</p> <ol style="list-style-type: none"> 1. GasSim determines the generation of methane gas, carbon dioxide and hydrogen produced using multiphase levels of first order decay equations. 2. Divided into 4 main modules: <ul style="list-style-type: none"> • Source term • Environmental transport and • Emissions • Exposure/impact 3. The methanogenic degradation of carbon is simulated by dividing the waste streams into three waste fractions (rapid, moderate and slow). 4. The model assumes that any LFG generated and not collected would be emitted through the landfill cap or liner at a steady state. 5. GasSim assumes that gas generated from an uncapped area, is not collected, and would be released through the surface to the atmosphere without methane oxidation. <p>Limitations:</p> <ol style="list-style-type: none"> 1. GasSim determines the quantity of trace gas generated by proportioning the concentration of the trace gas species to the LFG generation rate. 2. GasSim does not simulate: <ul style="list-style-type: none"> • Catastrophic impacts associated with inundation of floodwater, earthquake, or collapse of mine workings. • The movement of landfill leachate or LFG dissolved in water.

	<ul style="list-style-type: none"> • Acute events associated with sudden drops in atmospheric pressure resulting in lateral migration e.g asphyxiation and acute health effects by exposure to VOCs. • There is no biological oxidation of methane gas, dispersion, retardation or other attenuation/reaction processes that reduce the concentration of any gas as it moves through the ground. This will result in an overly conservative approach. • GasSim does not simulate the migration of dissolved gases.
Model name	LQM Model developed from the Department of Environment Food and Rural Affairs (DEFRA), UK, 2003
Team	LQM (Land Quality Management Limited) and ERM (Environmental Resource Management), UK
Equations used	<p>1. Methane gas generated in year t (Gg/yr) = $\sum_x [(A. k. MSW_T(x). MSW_F(x). L_0(x)). e^{-k(t-x)}]$-----IPCC 2000</p> <p>2. Methane gas generating potential, $L_0(x) = [MCF_{(x)}. DOC(x). DOC_{(F)}. F. 16/12](Gg CH_4/Gg waste)$-----IPCC 2000</p> <p>3. Methane gas emitted in year t (Gg/yr) = $[CH_4 \text{ generated in year } t - R(t)]. (1-OX)$ -----IPCC 2000</p> <p>4. Degradable Organic Carbon (DOC) and Fraction Dissimilated (DOC_F): $(DOC(x).DOC_{(F)})_{ij} = M(x)_{ij} (\%C_i + \%HC_i). \%DC_i. (1 - \%MC_i). 72/162$ (GgC/Gg waste) (Added in this model)</p> <p>5. Methane Oxidation: (developed a new model)</p> <ul style="list-style-type: none"> • Soil ($_{oxd cap}$) = $\nabla_{field\ eff} (SOC.24.365) A_{surface} M_m/M_v 10^{-9}$ [kt CH₄/y] • Avail$_{oxd cap}(x) = (1 - \nabla_{fissure})(CH_4 \text{ generated } (x) - R(t))$ [kt CH₄/y] • $A_{surface}(x) = \sum_{x=1}^{x=T} [WasteInput(x) / \rho(x)d_{site}(x)] 10^6$ • $OX = (1 - \nabla_{fissure})((CH_4 \text{ generated } (x) - R(t)) / (CH_4 \text{ generated } (x)))$
Components incorporated with the	<p>Assumptions:</p> <p>1. Methane gas generation rate was calculated considering the solid waste type as slowly degradable, moderately degradable, and rapidly degradable</p>

model	<p>waste (Brown et al. (1999)).</p> <p>2. Methane Correction Factor: $MCF_{(x)} = 1.0$ (managed solid waste disposal site) $= < 1$ (unmanaged solid waste disposal site)</p> <p>3. Fraction of Methane in LFG: $F = 0.5$ (Engineered design) $F = 0.3$ (Un Engineered design)</p> <p>4. Commercial and Industrial (C&I) waste streams were introduced alongside municipal solid waste (MSW) in this model.</p>
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Table 4 Other models summary on landfill gas generation and emissions.

Model name	UCF (LFG GEN) model
Team	University of Central Florida, USA
Equations used	<p>1. The equation for the peak rate: $G_P = L_0 * 2k / [k(T_P - T_L) + 2]$</p> <p>2. The biodegradation rate constant: $k = -\ln 0.01 / (T_F - T_P) = 4.6052 / (T_F - T_P)$</p> <p>3. Annual average methane gas generation rate:</p> <p>a. $G = 0 \quad 0 < t < T_L$</p> <p>b. $G = 1/2 G_P [(t - T_L) / (T_P - T_L) + (t - T_L) / (T_P - T_L)] \quad T_L < t < T_P$</p> <p>c. $G = 1/2 G_P [e^{-k(t-T_P)} + e^{-k(t-T_P)}] \quad T_P < t < T_F$</p> <p>5. Methane gas generating potential, $L_{0 CH_4} = (4a + b - 2c - 3d - 2e)_y / 8 \times (MW_{CH_4} / \cdot_{CH_4}) \times 1 / MW_y \times (1 - Ash_y) \times (1 - MC_y)$</p> <p>6. Carbon dioxide generating potential, $L_{0 CO_2} = (4a - b + 2c + 3d + 2e)_y / 8 \times (MW_{CO_2} / \cdot_{CO_2}) \times 1 / MW_y \times (1 - Ash_y) \times (1 - MC_y)$</p> <p>7. Biodegradability Factor = $0.83 - .028 X LC$</p>
Components incorporated with the model	<p>This is a user-friendly computer programmed model developed at UCF (University of Central Florida) to predict methane gas flux from any Florida landfill.</p> <p>Assumptions:</p> <p>1. Division of biodegradable solid waste into eleven categories were considered.</p>

	<p>2. Three moisture classifications - wet, moderate, and dry were adopted.</p> <p>3. Three biodegradability rates - rapid, moderate, and slow were simulated.</p> <p>4. LFGGEN can calculate trace gas annual average flux rates and mass generation.</p> <p>5. The model assumes that the trace gas is being generated in a constant proportion to the landfill gas.</p> <p>6. The model assumes that the gas that is generated in the landfill would be transported out.</p> <p>7. Used to estimate global impacts, methane gas recovery potential, provide input to a microscale air quality model.</p> <p>Limitation:</p> <p>1. The same equations for methane gas generation rate are used for carbon dioxide gas generation rate.</p>
Model name	Mexico landfill gas model
Team	SCS Engineers under contract to the U.S. EPA's, Landfill Methane Outreach Program (LMOP), 2003
Equations used	$Q_M = \sum_{i=1}^n 2 k L_o M_i (e^{-kt_i})$ <p>Where</p> $\sum_{i=1}^n = \text{sum from opening year (i=1) through year of projection, n}$ <p>Q_M = maximum expected LFG generation flow rate (m/yr) k = methane gas generation rate constant (1/yr) L_o = methane gas generation potential (m³/Mg) M_i = mass of solid waste disposed in the ith year (Mg) t_i = age of the waste disposed in the ith year (years)</p>
Components incorporated with the model	<p>The Mexico LFG Model is an Excel spreadsheet based on a first order decay equation developed with the help of US EPA's LandGEM model.</p> <p>Mexico LFG model calculates the maximum expected LFG generation and recovery potential.</p>

	<p>Factors considered in model:</p> <ul style="list-style-type: none"> • Amount of waste in place, • Methane gas generation rate (k), and • Waste acceptance rates, • Methane gas generation potential (L_0) <p>Assumptions:</p> <ol style="list-style-type: none"> 1. Time lag between the placement of waste and LFG generation is assumed to be one-year. 2. For each unit of waste, after one year the model assumes that LFG generation decreases exponentially as the organic fraction of waste is consumed. 3. Total landfill gas generation is estimated by doubling methane gas generation (the landfill gas is assumed to be half methane gas and half carbon dioxide). 4. It estimates the energy content of generated landfill gas in Giga joules per year (G J/yr). 5. The model provides the default values for k and L_0. <p>Limitation:</p> <ol style="list-style-type: none"> 1. Modeling landfill gas generation and recovery accurately is difficult due to the limitations in available information for inputs data to the model.
Model Name	The Scholl-Canyon model
Team	USA
Equations used	<ol style="list-style-type: none"> 1. CH_4 generation rate at time t: $Q_{CH_4} = L_0 * R * (e^{-k_c} - e^{-k t})$ 2. $Q = 2 * k * L_0 * R * (e^{-k(t-lag)})$ (The refined Scholl Canyon Model equation)
Components incorporated with the model	<p>Scholl Canyon model is first order decay model.</p> <p>Assumptions:</p> <ol style="list-style-type: none"> 1. The Scholl Canyon Model assumes that methane generation is a function of first-order kinetics. 2. This model ignores the first two stages of bacterial activity and is simply based on the observed characteristics of substrate-limited bacterial growth. 3. The gas production rate is assumed to be at its peak rate based on initial

	<p>placement after a negligible lag time. During that time anaerobic conditions are established and decreases exponentially (first-order decay) as the organic content of the waste is consumed.</p> <p>4. The model is dependent on the following factors that affect biodegradation rates:</p> <ul style="list-style-type: none"> • Age of waste, • Moisture content. • Average annual placement rates are used <p>5. The model uses two adjustable variables namely L_0 and k.</p> <p>Limitation:</p> <p>1. The model is impractical for use global scale where site-specific data are not available.</p>
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Table 5 Different types of waste categories used for the analysis of the RLFGM model

Degradability	Waste Fraction
Rapid (RDO)	Paper and Card
	Textiles
	Misc. Combustible (plus non inert)
Moderate (MDO)	Composted putrescible
	Ferrous Metal
	Non Ferrous Metal
Slow (SDO)	Dense Plastics
	Misc. Non Combustible (Plus inert fines)
	Glass

Table 6 MSW waste (Mt) used in the simulation of RLFGM model (Data Source Barlaz et al. (1997), Bellingham et al. (1994), environment agency UK 2002a, department of the environment UK, 1994 a, b and some of them are defined by the developer). The table shows the input data for year 1995 to year 2000 years. The simulation was performed for thirty years.

Waste Acceptance Year	2000	1999	1998	1997	1996	1995	Year	
Acceptance Rates, Mt/yr	8.27	8.65	8.30	8.36	7.92	7.63	Paper and Card RDO	Waste Category
%MC _i	31.35	31.98	31.41	31.60	31.00	30.00		
%C _i (%DW)	61.32	62.00	61.312	61.36	61.30	61.20		
%HC _i (%DW)	9.55	9.78	9.66	9.566	9.12	9.10		
%DC _i	61.89	62.10	61.90	61.92	61.81	61.80		
Acceptance Rates, Mt/yr	0.58	0.59	0.54	0.52	0.50	0.48	Textiles – RDO	
%MC _i	26.94	26.98	26.674	26.60	26.00	25.00		
%C _i (%DW)	21.86	22.00	21.00	20.876	20.50	20.00		
%HC _i (%DW)	20.90	21.00	20.756	20.675	20.50	20.00		
%DC _i	50.58	50.59	50.253	50.253	50.10	50.00		
Acceptance Rates, Mt/yr	2.46	2.16	2.08	2.09	1.98	1.91	Misc. Combustible (Plus Non Inert Fines) – RDO	
%MC _i	21.94	21.78	21.14	21.20	21.00	20.00		
%C _i (%DW)	26.78	26.00	25.75	25.84	25.50	25.00		
%HC _i (%DW)	26.12	25.89	25.56	25.67	25.40	25.00		
%DC _i	51.345	51.00	50.786	50.786	50.32	30.00		

Waste Acceptance Year	2000	1999	1998	1997	1996	1995	Year	
Acceptance Rates, Mt/yr	5.53	5.68	5.45	5.49	5.20	5.00	Composted Putrescible - RDO	Waste Category
%MC _i	30.96	31.00	30.82	30.90	30.60	30.00		
%C _i (%DW)	0.745	0.823	0.698	0.712	0.712	0.700		
%HC _i (%DW)	0.823	0.845	0.717	0.720	0.700	0.700		
%DC _i	57.95	58.10	57.83	57.83	57.00	57.00		
Acceptance Rates, Mt/yr	1.38	1.48	1.56	1.57	1.49	1.43	Ferrous Metal - MDO	
%MC _i	5.10	4.99	5.20	5.21	5.00	5.00		
%C _i (%DW)	0.00	0.00	0.00	0.00	0.00	0.00		
%HC _i (%DW)	0.00	0.00	0.00	0.00	0.00	0.00		
%DC _i	0.00	0.00	0.00	0.00	0.00	0.00		
Acceptance Rates, Mt/yr	0.57	0.57	0.52	0.52	0.50	0.48	Non Ferrous Metal - MDO	
%MC _i	11.56	11.50	10.76	10.78	10.50	10.00		
%C _i (%DW)	0.00	0.00	0.00	0.00	0.00	0.00		
%HC _i (%DW)	0.00	0.00	0.00	0.00	0.00	0.00		
%DC _i	0.00	0.00	0.00	0.00	0.00	0.00		

Waste Acceptance Year	2000	1999	1998	1997	1996	1995	Year	
Acceptance Rates, Mt/yr	3.35	2.97	2.85	2.88	2.72	2.62	Dense Plastics -SDO	Waste Category
%MC _i	6.50	5.95	5.76	5.80	5.00	5.00		
%C _i (%DW)	0.00	0.00	0.00	0.00	0.00	0.00		
%HC _i (%DW)	0.00	0.00	0.00	0.00	0.00	0.00		
%DC _i	0.00	0.00	0.00	0.00	0.00	0.00		
Acceptance Rates, Mt/yr	2.40	2.43	2.33	2.35	2.34	2.14		
%MC _i	5.29	5.33	5.02	5.05	5.00	5.00		
%C _i (%DW)	0.00	0.00	0.00	0.00	0.00	0.00		
%HC _i (%DW)	0.00	0.00	0.00	0.00	0.00	0.00		
%DC _i	0.00	0.00	0.00	0.00	0.00	0.00		
Acceptance Rates, Mt/yr	2.43	2.33	2.34	2.35	2.23	2.14	Glass – SDO	
%MC _i	5.240	5.019	5.019	5.018	5.000	5.000		
%C _i (%DW)	0.00	0.00	0.00	0.00	0.00	0.00		
%HC _i (%DW)	0.00	0.00	0.00	0.00	0.00	0.00		
%DC _i	0.00	0.00	0.00	0.00	0.00	0.00		

Continue Table 6

Table 7 Waste degradation rate constants

	Rate constant, k (per year) also expressed as a half life, $t_{1/2}$ (years)					
	Manely et al. (1990a; 1990b)		Brown et al. (1999)		GasSim (Environmental Agency 2002a), RLFGM used these values for the implementation purpose	
	K	$t_{1/2}$	K	$t_{1/2}$	K	$t_{1/2}$
Rapidly Degradable Organic	0.69	1	0.185	3.75	0.116	6
Moderately Degradable Organic	0.14	5	0.1	6.9	0.076	9
Slowly Degradable Organic	0.05	~15	0.05	~15	0.046	15

Table 8 SWDS (Solid Waste Disposal Sites) classification and methane correction factors

Type of Site	Methane Correction Factor
Managed	1
Unmanaged (deep, $\geq 5m$ waste)	0.8
Unmanaged (shallow, $< 5mm$ waste)	0.4
Default Value (Uncategorized SWDS)	0.6

Table 9 Typical landfill gas compositions at methanogenic phase

Gas Component	Component Content (% by volume)
Methane	45.00 – 60.00%
Carbon Dioxide	40.00 – 60.00%
Nitrogen	2.00 – 5.00%
Oxygen	0.10 – 1.0%
Ammonia	0.10 – 1.0%
Hydrogen	0.00 – 0.20%

Table 10 Calculated DOC(x).DOC_F values based on data input in Table 6. Measured unit Gg C/Gg waste

Year	Paper and Card - RDO	Textiles – RDO	Misc. Combustible (Plus Non Inert Fines) – RDO	Compos- -fed putre scible – RDO	Ferrous Metal - MDO	Non Ferrous Metal - MDO	Dense Plastics - SDO	Misc. Non Com- bustible Plus Inert Fines – SDO	Glass - SDO
1995	0.0010313	0.000032	0.0001698	1.241E-05	0.00	0.00	0.00	0.00	0.00
1996	0.0010572	3.378E-05	0.0001781	1.291E-05	0.00	0.00	0.00	0.00	0.00
1997	0.0011161	3.542E-05	0.0001915	1.397E-05	0.00	0.00	0.00	0.00	0.00
1998	0.0011116	3.693E-05	0.0001900	1.373E-05	0.00	0.00	0.00	0.00	0.00
1999	0.0011656	4.165E-05	0.0001987	1.688E-05	0.00	0.00	0.00	0.00	0.00
2000	0.0011067	4.073E-05	0.0002318	1.542E-05	0.00	0.00	0.00	0.00	0.00
2001	0.0010493	3.990E-05	0.0002293	1.340E-05	0.00	0.00	0.00	0.00	0.00
2002	0.0009935	3.859E-05	0.0002266	1.105E-05	0.00	0.00	0.00	0.00	0.00
2003	0.0009306	3.680E-05	0.0002233	1.121E-05	0.00	0.00	0.00	0.00	0.00
2004	0.0008346	3.771E-05	0.0002200	9.806E-06	0.00	0.00	0.00	0.00	0.00
2005	0.0008264	3.851E-05	0.0002242	1.029E-05	0.00	0.00	0.00	0.00	0.00
2006	0.0008229	3.860E-05	0.0002256	1.149E-05	0.00	0.00	0.00	0.00	0.00
2007	0.0008210	3.949E-05	0.0002295	1.096E-05	0.00	0.00	0.00	0.00	0.00
2008	0.0008039	3.940E-05	0.0002384	1.044E-05	0.00	0.00	0.00	0.00	0.00
2009	0.0007795	3.454E-05	0.0002388	9.845E-06	0.00	0.00	0.00	0.00	0.00
2000	0.0006988	3.247E-05	0.0002167	8.706E-06	0.00	0.00	0.00	0.00	0.00
2011	0.0006079	2.716E-05	0.0001925	7.123E-06	0.00	0.00	0.00	0.00	0.00
2012	0.0005252	2.216E-05	0.0001638	5.901E-06	0.00	0.00	0.00	0.00	0.00
2013	0.0004440	1.819E-05	0.0001386	4.450E-06	0.00	0.00	0.00	0.00	0.00
2014	0.0003683	1.718E-05	0.0001351	3.381E-06	0.00	0.00	0.00	0.00	0.00
2015	0.0003511	1.692E-05	0.0001125	3.035E-06	0.00	0.00	0.00	0.00	0.00
2016	0.0003406	1.691E-05	0.0001107	2.856E-06	0.00	0.00	0.00	0.00	0.00
2017	0.0003286	1.624E-05	0.0001086	2.629E-06	0.00	0.00	0.00	0.00	0.00
2018	0.0003153	1.555E-05	0.0001055	2.302E-06	0.00	0.00	0.00	0.00	0.00
2019	0.0003032	1.551E-05	0.0001034	1.905E-06	0.00	0.00	0.00	0.00	0.00
2020	0.0002916	1.545E-05	0.0001005	1.662E-06	0.00	0.00	0.00	0.00	0.00
2021	0.0002760	1.479E-05	9.733E-05	1.542E-06	0.00	0.00	0.00	0.00	0.00
2022	0.0002623	1.414E-05	9.199E-05	1.336E-06	0.00	0.00	0.00	0.00	0.00
2023	0.0002471	1.347E-05	8.880E-05	1.168E-06	0.00	0.00	0.00	0.00	0.00
2024	0.0002213	1.279E-05	8.439E-05	7.239E-07	0.00	0.00	0.00	0.00	0.00
2025	0.0002060	1.178E-05	7.515E-05	3.523E-07	0.00	0.00	0.00	0.00	0.00

Table 11 Sample output of RLFGM model implementation for methane gas generating potential (L_0). Measured unit Gg CH_4 /Gg Waste

Year	$L_0(x)$ – RDO	$L_0(x)$ – MDO	$L_0(x)$ – SDO	Year	$L_0(x)$ – RDO	$L_0(x)$ – MDO	$L_0(x)$ – SDO
1995	0.0008303	0.00	0.00	2011	0.0134700	0.00	0.00
1996	0.0016849	0.00	0.00	2012	0.0139481	0.00	0.00
1997	0.0025896	0.00	0.00	2013	0.0143516	0.00	0.00
1998	0.0034911	0.00	0.00	2014	0.0147009	0.00	0.00
1999	0.0044397	0.00	0.00	2015	0.0150233	0.00	0.00
2000	0.0053695	0.00	0.00	2016	0.0153373	0.00	0.00
2001	0.0062574	0.00	0.00	2017	0.0156414	0.00	0.00
2002	0.0071039	0.00	0.00	2018	0.0159338	0.00	0.00
2003	0.0079052	0.00	0.00	2019	0.0162165	0.00	0.00
2004	0.0086399	0.00	0.00	2020	0.0164893	0.00	0.00
2005	0.0093728	0.00	0.00	2021	0.0167491	0.00	0.00
2006	0.0101052	0.00	0.00	2022	0.0169956	0.00	0.00
2007	0.0108392	0.00	0.00	2023	0.0172293	0.00	0.00
2008	0.0115673	0.00	0.00	2024	0.0174421	0.00	0.00
2009	0.0122757	0.00	0.00	2025	0.0176376	0.00	0.00
2010	0.0129135	0.00	0.00				

Table 12 Parameters from RLFGM model used for the simulation of the LandGEM model for the purpose of model verification

Parameters	Value
Methane Generating potential, L_0	$L_0 = 100 \text{ m}^3/\text{Mg}$
Methane content	50% (by volume)
Methane generation rate constant, k (for RDO)	0.116 year^{-1}
Solid waste components	From Table 6 (RDO component only)

Table 13 Methane gas emission rates from RLFGM model and LandGEM model.

Year	Methane gas emission rate (RLFGM), Gg/yr	Methane gas emission rate (LandGEM), Mg/yr	Methane gas emission rate (LandGEM), Gg/yr	Year	Methane gas emission rate (RLFGM), Gg/yr	Methane gas emission rate (LandGEM), Mg/yr	Methane gas emission rate (LandGEM), Gg/yr
1995	9.673E-10	0	0	2011	1.325E-09	8.037E-04	8.037E-07
1996	1.886E-09	1.104E-04	1.104E-07	2012	9.549E-10	7.968E-04	7.968E-07
1997	2.873E-09	2.129E-04	2.129E-07	2013	6.543E-10	7.813E-04	7.813E-07
1998	3.411E-09	3.106E-04	3.106E-07	2014	4.564E-10	7.577E-04	7.577E-07

1999	4.205E-09	3.969E-04	3.969E-07	2015	3.725E-10	7.290E-04	7.290E-07
2000	4.403E-09	4.789E-04	4.789E-07	2016	3.224E-10	7.005E-04	7.005E-07
2001	4.181E-09	5.503E-04	5.503E-07	2017	2.775E-10	6.739E-04	6.739E-07
2002	3.827E-09	6.084E-04	6.084E-07	2018	2.361E-10	6.489E-04	6.489E-07
2003	3.379E-09	6.544E-04	6.544E-07	2019	2.028E-10	6.251E-04	6.251E-07
2004	2.909E-09	6.891E-04	6.891E-07	2020	1.726E-10	6.026E-04	6.026E-07
2005	2.835E-09	7.136E-04	7.136E-07	2021	1.445E-10	5.812E-04	5.812E-07
2006	2.726E-09	7.359E-04	7.359E-07	2022	1.205E-10	5.605E-04	5.605E-07
2007	2.604E-09	7.559E-04	7.559E-07	2023	1.004E-10	5.403E-04	5.403E-07
2008	2.460E-09	7.736E-04	7.736E-07	2024	7.790E-11	5.208E-04	5.208E-07
2009	2.237E-09	7.891E-04	7.891E-07	2025	5.581E-11	5.005E-04	5.005E-07
2010	1.771E-09	8.011E-04	8.011E-07				

Table 14 Comparison between RLFGM and LandGEM model

Parameters	RLFGM model	LandGEM model
Equations	Model uses multilevel phases of equations for the generation and emission of methane gas from landfills (equation 2.1 to 2.4)	Model uses first order decay equation (Appendix A, Table 1)
Waste Category	Model uses three types of waste components as rapidly degradable, moderately degradable and slowly degradable organic making up nine waste fractions as paper and textiles, misc. combustible (plus non inert), composted putrescible, ferrous metal, non ferrous metal, dense plastics, misc. non combustible (plus inert fines) and glass.	All waste components having the potential to generate methane gas have been used. Only rapidly degradable organic has been used for the simulation purpose as moderately degradable and slowly degradable organic component have very little possibility to generate methane gas.
Methane gas generation rate constants	Three methane gas generation rate constants were used as 0.116 (for rapidly degradable organic), 0.076 (for moderately degradable organic) and 0.046 (for slowly degradable organic)	One methane gas generation rate constant 0.116 year ⁻¹ from RLFGM model was used for simulation considering the fact that primarily rapidly degradable organic components generate methane gas.
Methane gas generation potential	The major difference between RLFGM model and LandGEM model is the calculation for the methane generating potential (L_0)	The model uses 100 m ³ /Mg as the methane generating potential L_0 value for the simulation purpose.

	<p>which controls the methane gas generation rate. For the development of RLFGM model equations 2.1 to 2.3 have been used. The equations state that methane gas generation potential is based on the calculation of $DOC(x).DOC_{(F)}$. The term degradable organic carbon (DOC) and fraction dissimilated (DOC_F) is defined by moisture content, cellulose, hemi-cellulose and degradability fraction of cellulose and hemi-cellulose of individual waste category. The calculated methane generating potential (L_0) have been used for the calculation of methane gas generation in the model.</p>	
Lignin component	Lignin component is not considered for the calculation of $(DOC(x).DOC_F)$ based on comprehensive literature review.	As the model does not go for the calculation of methane generating potential (L_0) value, it is not obvious that lignin component has been considered for defining the methane generating potential.
Methane gas emission rate	Methane gas emission rate output was lower (Appendix A, Table 13) than LandGEM output.	Methane gas emission rate output found higher compared to RLFGM model output in the simulation (Appendix A, Table 13).